UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
WASHINGTON, D. C.

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This paper was presented in abstract form at the meetings of the American Geophysical Union in April 1940. It is reproduced here in more complete form to include field procedure and methods of analysis used in deriving hydrologic values.

SPRINKLED PLAT RUN-OFF AND INFILTRATION EXPERIMENTS ON ARIZONA DESERT SOILS.

Edward L. Beutner, Ralph R. Gaebe
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Introduction: The original objectives of sprinkled plat experiments conducted by the Soil Conservation Experiment Station at Tucson were to determine infiltration capacities of a number of important soil types found on range lands on the watersheds of southern Arizona and to evaluate surface soil conditions and various types of native plant covers and their management in terms of their influence on erosion and infiltration. These problems necessarily involve many variables which must receive careful study and be subjected to replication of experiments. However, from the beginning of this work it was noted that hydrographs secured lent themselves very well to analysis and showed a good agreement with the analytical treatment of surface run-off phenomena from plats as reported by Dr. R. E. Horton.[1] For this reason it was thought advisable to conduct each experiment in such a way that complete hydrologic data might be secured in addition to any other data which might be desired. This has made it possible to study hydrographs of a large

[1]Horton, Robert E., Analysis of runoff plat experiments with varying infiltration-capacity. Trans. A. G. U. 1939, pp. 693-711.

number of experiments as well as provide data for studies of soil, erosion, and plant relationships.

The experiments reported herein are based on 94 separate applications of controlled amounts and intensities of artificial rain on plats 6 feet by 24 feet in size. Most of the experiments were conducted on sparsely vegetated or bare soils characteristic of millions of acres lying in the semi-desert portions of the Gila, Rio Grande and lower Colorado River watersheds. A second series of experiments is being conducted at the present time in areas of the semi-desert grassland where ecological relationships between plant cover, soil erosion, and infiltration are under study.

The discussion and interpretations presented in this paper will be limited largely to hydrologic relationships and related factors which bear directly on hydrologic phenomena.

Procedure in selecting sites and plats: Due to the variety of topographic, soil, climate, and plant conditions found in southern Arizona it is evident that controlled plat experiments may not include all types of country. Physical limitations made it advisable to conduct the experiments in lower watershed areas which are or might be included in a soil and water conservation program and for which little information is at present available. Maps of soil and range conservation surveys were studied and technicians dealing with surveys and treatment of watershed areas were consulted in order to select important areas for study. Accessibility and location within reasonable distance to

a suitable water supply were other factors which influenced the selection of study sites.

After a study site was located, plat locations were established. Plats were duplicated for each condition to be studied and sometimes replicated more if preliminary studies showed marked variation.

Description of sprinkler apparatus: A sprinkler system, similar in most respects to the D-1 apparatus designed by the Soil Conservation Service in cooperation with the Bureau of Standards in Washington, was used in these experiments. The apparatus consists essentially of four stationary 1.5 "Mulsifyre" nozzles mounted on an overhead frame by which water may be applied at constant rates to a plat 6 feet wide and 24 feet long (Figure 1). With two nozzles in operation, water is applied at a rate slightly in excess of three inches per hour and with four nozzles discharging, at a rate of about six inches per hour. Since slight variations in rate of application due possibly to changes of temperature, pressure, elevation, or mechanical operation were noted in calibrating the apparatus, check runs are made on each site to determine the exact rate of application. This is accomplished by covering a plat with a waterproofed canvas, applying rainfall, and measuring the rate and volume of run-off which is complete and thus equals rainfall. Satisfactory distribution of water is obtained with drop sizes comparable to actual rainfall,

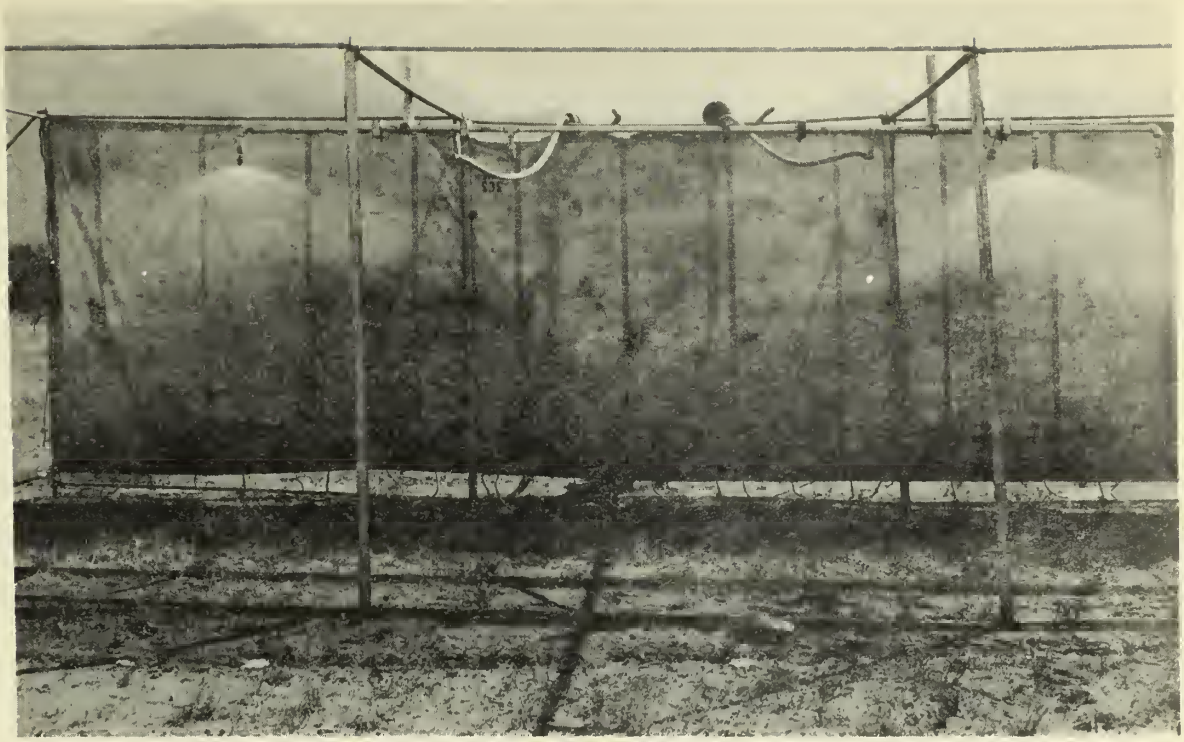

Figure 1.--Sprinkler apparatus in operation.

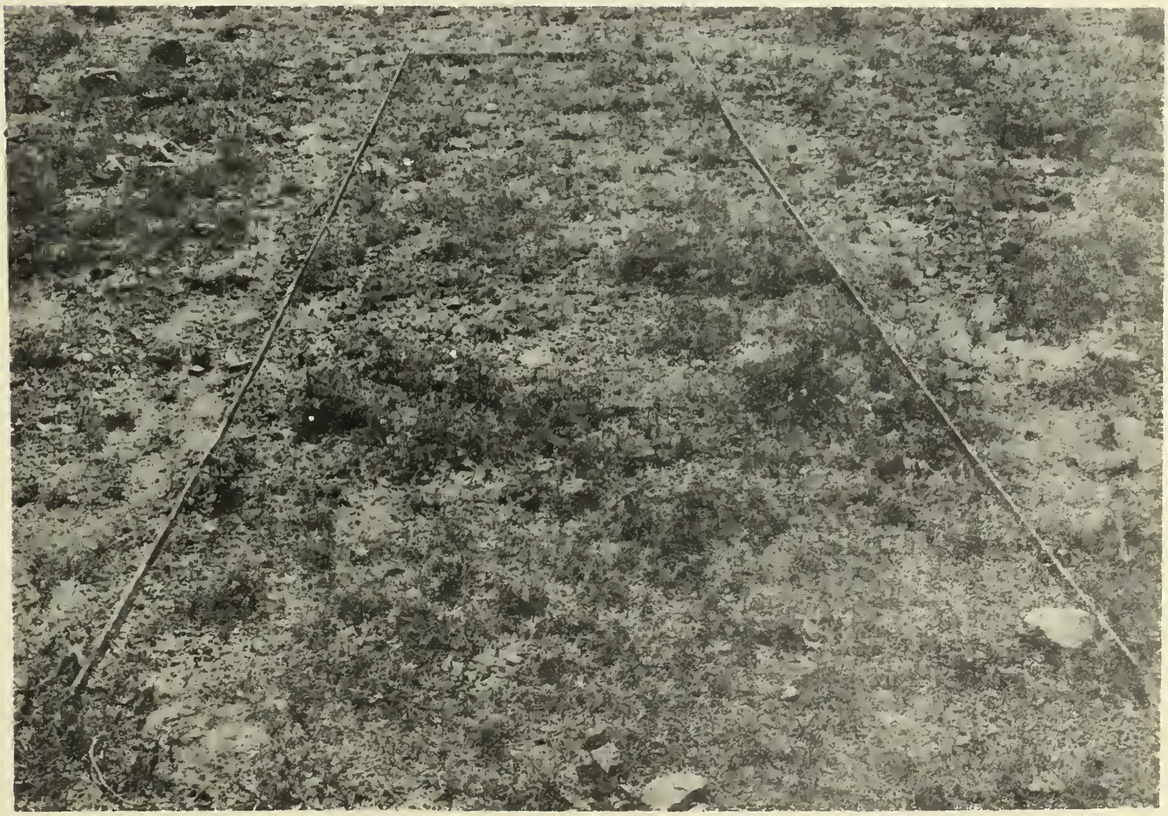

Figure 2.--Upper and side boundaries of a plat in place.

a study of the characteristics of drops indicating an effective size of about 1.6 mm.

The study plat is enclosed on three sides by 6-inch boundary plates which extend 4 inches below the surface (Figure 2). A strip 18 inches wide adjacent to the sides and upper end of the plat receives the same rain application as the plat to reduce any border effect. An end plate and collecting trough at the lower end of the plat serve to concentrate run-off which is discharged into calibrated measuring tanks (Figure 3). Accurate timing of increments of run-off is made so that rate of run-off may be calculated. A small flume would give instantaneous rates of run-off but because of interference caused by debris and silt and the difficulty of getting enough readings on rapidly rising and falling stages of run-off, the volumetric method of measurement was adopted. Holes with rubber stoppers are placed in the bottoms of the collecting tanks for discharging water into a sump hole after measurement is made.

The entire sprinkling apparatus and study plat are enclosed with canvas curtains to provide a shield from winds which tend to reduce uniformity of application (Figure 4).

Water is supplied from two carrying tanks mounted on a truck and trailer. It is first allowed to flow to a sump tank where it is maintained at a uniform level by means of a float valve. From these it is pumped to the applicator under a pressure

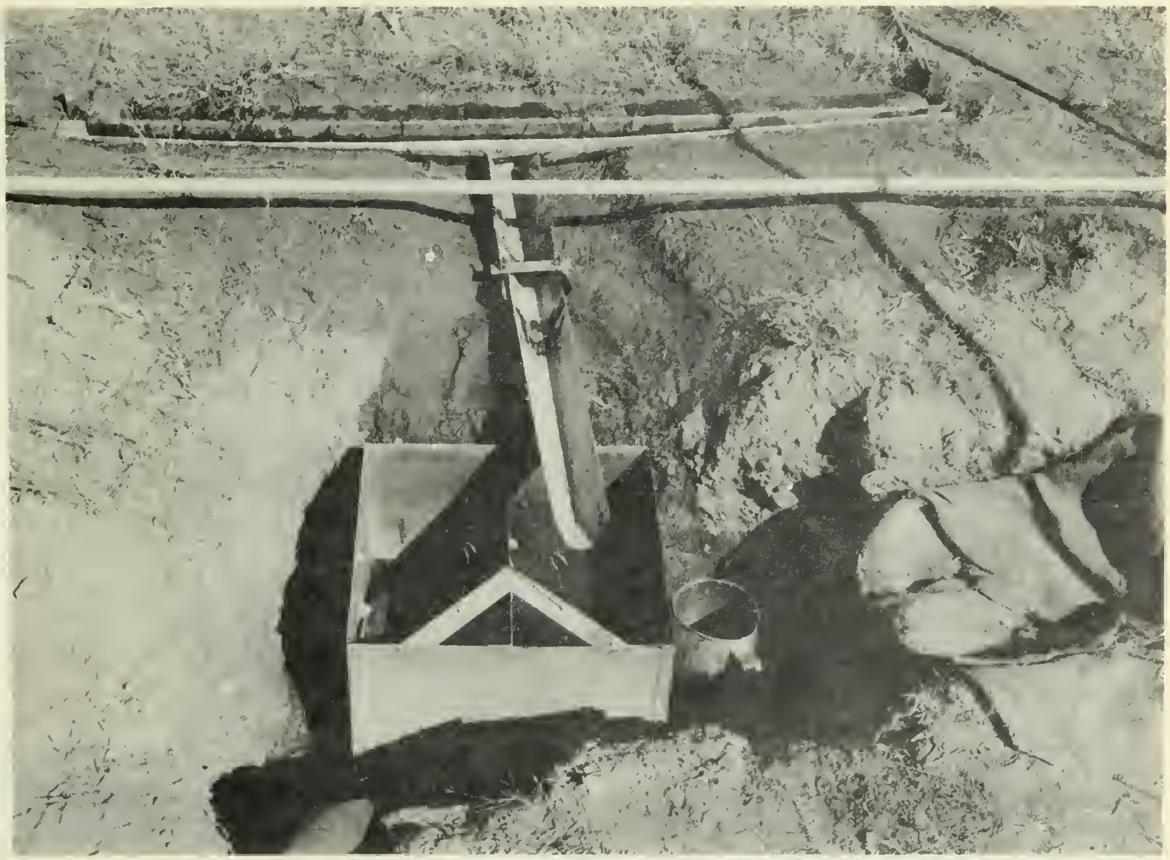

Figure 3.--End plate, collecting trough, and containers for measuring runoff.

Figure 4.--Complete field setup with sprinkler apparatus and plat enclosed by canvas shield.

of 5.5 pounds held constant by means of proper adjustment of pressure valves.

Methodology of conducting experiments: Plat boundaries of wood or steel are placed by removing dirt to a depth of 4 inches starting about 3 inches from outside of plat boundary and working up to the plat line (Figure 5). Most of the disturbance is thus confined to the area outside the plat. If rocks are encountered within 4 inches of the soil surface, wood boundaries are used and are cut to fit around the rock, and asphalt patching cement is used to make the joint around the rock watertight. It is estimated that only one to three percent of a plat area is disturbed as a result of the installation of boundaries, and the area disturbed is returned nearly to normal by refilling and lightly tamping the displaced soil.

An attempt was made to use steel boundaries driven into the ground instead of excavating a trench as shown in Figure 5, but the results were not satisfactory in that even under ideal conditions for driving, there was considerable disturbance of the soil near the boundary, and if rock, hardpan or very dense clay were encountered, the driving process was impossible.

Before each experiment a five minute check run is made on a waterproof canvas to be sure that the apparatus is in good working order and to check rate of application. After the check run has been completed and everything found to be in good working order, the ground canvas is removed and soil and air temperature taken.

Figure 5.--Method of placing plat boundaries.

In this discussion, the initial or dry run is the first run made on a plat in which soil moisture and surface conditions are similar to those outside the plat. The second or wet run is made approximately twenty-four hours later when soil moisture has reached equilibrium being near field capacity as a result of the initial application of water.

Before the initial run on a plat the soil moisture can be assumed to be fairly uniform throughout a site and so moisture samples are taken outside of the plat to avoid unnecessary disturbance. In the case of the wet run the soil samples have to be taken within the plat boundaries. The number and depth of samples taken varied considerably for the early experiments because of an attempt to sample according to soil horizons, but in later experiments soil moisture samples were taken from 0 to 2", 2" to 4", and from 4" to a variable depth depending on the thickness of the soil mantle on any particular site. Three samples were taken before each experiment except when very stony conditions made it impossible to get samples below 4 inches without excessively disturbing the plat.

When all of the preliminary work is completed the observer takes a position most advantageous for studying the plat and application is started. At first the rate of intake of water by the soil is equal to rate of application, but after a short time rate of intake drops below rate of application and water begins to accumulate in depressions and finally moves toward the lower end of

the plat (Figure 6). The period during which i = f (intake equals application) is noted and the time when most of the depressions are filled and water movement starts is also noted. Shortly after water movement has started run-off occurs and measurements are started. The rate of run-off is determined in inches per hour by noting time required for various increments of run-off as measured accumulatively in measuring cans and tank. For rising and falling stages of run-off measurements are made in as small an increment as can be accurately measured and timed, but for nearly constant rate of run-off the increments of measurement are increased to include 2 to 4 minutes.

Soil erosion is determined from run-off samples taken at various intervals throughout the run-off period. The samples are taken by collecting all of the run-off for the very short period of time necessary to fill pint sample jars. In most of the experiments reported in this paper soil losses were due to sheet erosion and in only a few cases was gully erosion induced by application of rain. Since the soil losses were not large in most of the experiments, it is believed that the volume of soil in the run-off did not materially affect the volumetric measurements of the latter.

For the early experiments the total time of application was controlled largely by the available water supply and was often limited to one half hour. In most cases the rate of run-off became constant before the end of a half hour.

Figure 6.--Surface of upper portion of plat showing depressions filled and water movement starting. Lower end of plat is to the left.

After application has stopped and residual run-off is complete, an estimate of remaining depression storage is made, the soil, air, and water temperatures are taken and depth of penetration is measured. After the last experiment has been completed and no further need is anticipated for a plat, trenches are dug across it to study the penetration pattern and to ascertain boundary effect on penetration. There was no boundary effect when average penetration exceeded 8 inches, and only very little evidence showing increased depth of penetration along boundaries for average depth of penetration of 4 to 8 inches, but when average depth of penetration was less than 4 inches, boundary effect was apparent. The first three cross sections (Figure 7) show typical patterns of penetration which are reached after the second or wet run in many of the experiments. The second set of three cross sections is typical when average depth of penetration is 4 inches or less as would sometimes be the case immediately after the first run on a dry plat.

Description of soils and profiles: Most of the experiments were conducted on soils developed under semiarid conditions in the vicinities of Safford and Tucson, Arizona, and characteristic of rather large areas of the lower valley and mesa lands of southern Arizona. They belong to the reddish brown, Shantung brown, and red desert groups. Topographically the soils occur on mesas and lower foothill slopes and in alluvial swales or broad valley bottoms. The latter soils are usually of heavier texture than the former and when

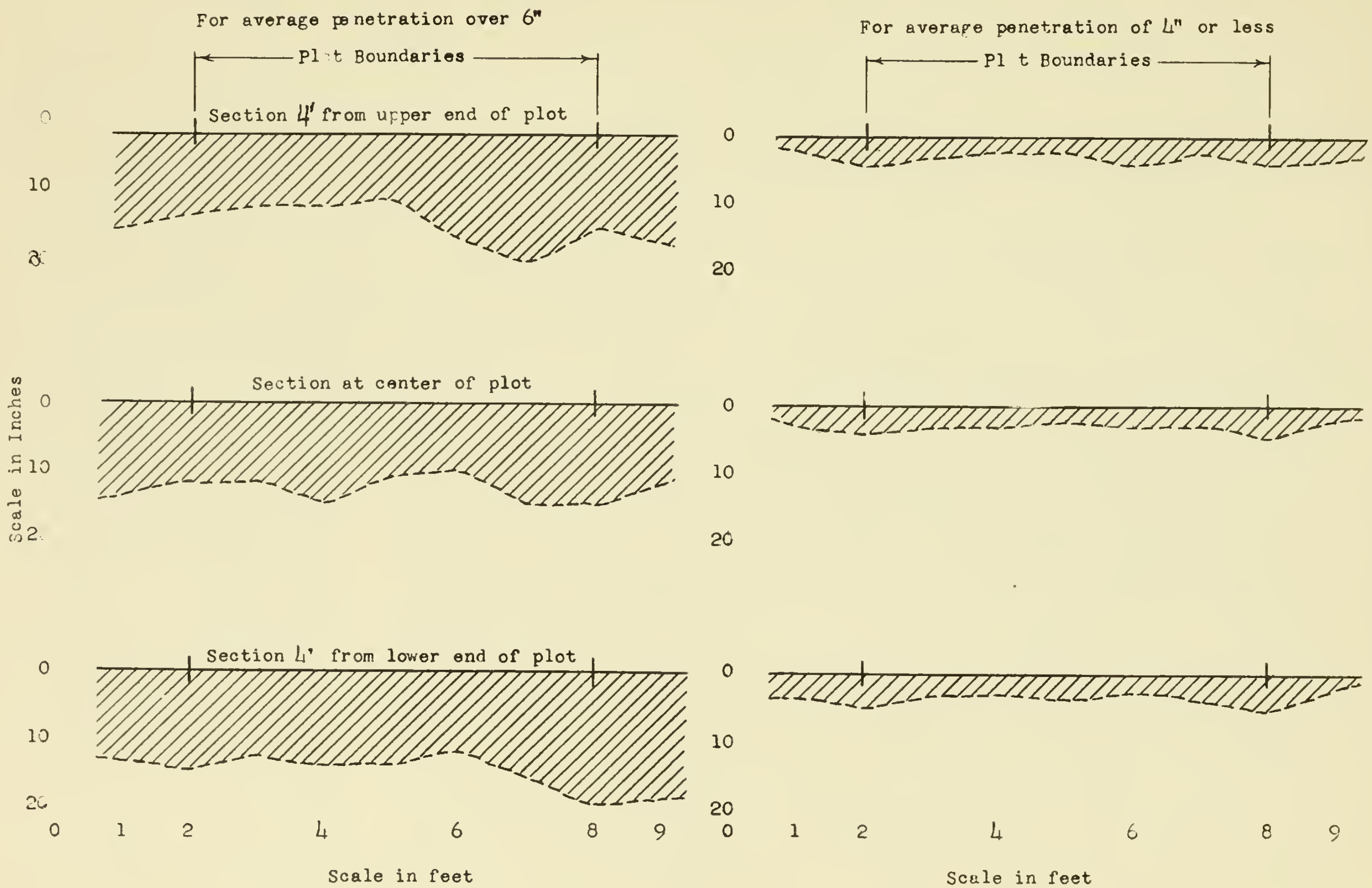

FIGURE 7.--Typical cross-sections showing penetration depths

unprotected by vegetation tend to puddle and seal over rapidly under the impact of rain drops and running water. With one or two exceptions the soil sites studied are at present sparsely vegetated though ecological studies indicate that many of them at one time supported a more luxuriant growth of perennial grasses. Where unprotected by a good vegetative cover the present soil surface is the result of action of water and wind as well as of the effect of occasional trampling by livestock. In many cases it is probably quite different from the condition found before livestock utilized the range heavily which tended to diminish the density of plant cover and accelerate the removal of the surface soil
With these processes a gradual lowering of infiltration capacities of the soils appears to have taken place. While many surfaces have again become fairly well stabilized as far as sheet erosion is concerned due to the development of protective erosion pavements, increased local run-off undoubtedly is one of the major factors contributing to arroyo cutting and its many ramifications in the valley and tributary bottom lands.

The soils studied vary from nearly pure sands to clay loams although the majority of them fall into the sandy and gravelly loam textures as do the larger areas in the field. Development of compact layers in the subsoil is characteristic of most of the upland soils. Table 1 outlines briefly the field characteristics of the soils studied.

<u>Results of the experiments</u>: Results of the individual experiments are given, together with the results of the analysis, on Table 2. This table contains the results of all experiments excepting those where, owing to pump trouble or other causes, the experiment was incomplete, and a few experiments made with a rain intensity of 6 inches or more per hour, where active erosion developed and the results are not comparable with the other experiments. These experiments are reserved for separate analysis.

The following notes give the notation used in the column headings and explain both the meanings of the terms and the methodology of analysis of the experiments.

Col. 6 - Initial moisture content of the soil surface, 0 - 2 inches depth, except as noted - percent of dry weight.

Col. 7 - Initial moisture content, 0 - 6 inches depth, percent of dry weight, obtained by adding the moisture content 0 - 2 inches to twice the moisture content 2 - 6 inches depth and dividing by 3.

Col. 8 - Moisture equivalent at 1,000 times gravity, determined by standard laboratory method.

Cols. 9, 10, 11, temperature °F., at beginning of experiment.

Col. 12, i, average rain intensity, inches per hour; obtained by dividing total rainfall by duration of rain application in hours. Rain intensity was maintained sensibly constant throughout each experiment.

TABLE 1. Field Description of Sites and Soils Studied

Site No.	Soil type	Surface Soil	Subsoil	Topography & Origin	Degree of Erosion	Cover
5 6 7	Mohave gravelly sandy loam	Reddish brown, gritty friable calcareous	Redder, finer texture more compact. Lime accumulations	Rolling to flat topped terraces and fans. Largely from granite	Slow sheet erosion. Coarse sand and fine gravel erosion pavement	None, except for very little annual plant litter
10	Gila fine sandy loam	Light brown to pinkish brown, calcareous,	Light colored, stratified recent stream deposits	Recent bottom soils. Mixed origin	Severe sheet erosion "A" horizon 2" to 4"	None
11	"	"	"	"	Sandy overwash "A" horizon 6" to 10"	Very sparse Few burroweeds present were removed
12	"	"	"	"	No recent erosion "A" horizon 8" to 10"	
13	Gila silt loam	"	"	"	No recent erosion	Some annual plants and litter
14	Cajon sand	Light grayish brown, calcareous, coarse	Similar to surface Deep stratified, sandy deposits	Alluvial fans and flood plains outwash from granite rocks	No recent erosion	Some filaree and litter
15	Ramona sandy clay loam	Brown to grayish brown, gritty surface soil	Heavier moderately compact, grading to gravelly sediments	Upper and lower fans. From granitic materials	Recent overwash Surface badly checked	None
16	"	"	"	"	Slight erosion, fine gravelly erosion pavement	Fair cover annual plants and litter
18	Mohave sandy clay loam	Reddish brown gritty, friable calcareous	Redder, finer texture very compact	Lower fans and terraces, Derived from granite	Slight sheet erosion	Sparse weed cover
19	Teague stony loam	Grayish brown, calcareous. Very rocky	Dark brown calcareous Clay loam. Caliche hardpan	Alluvial fans and terraces. Derived from basalt	Gravelly erosion pavement	None
20	White house stony loam	Friable, granular dull-brown	Tough red clay Cobbly	Upper fans. Granite origin	Moderate sheet erosion. Stony pavement	Sparse cover of caliandra and grama gras
21	Sonoita sandy loam	Reddish-brown medium to coarse	Compact heavy clay loam	Alluvial fans Rhyolitic origin	Slight erosion	Sparse cover annual plants, Some litter

ZONA

Date	Site No.	Plat No.	Run No.	St… Pe… …rv. …1.	Ratio Q_r-Calc. / Q_r-Obs'd.	$q_e t_r$	Q_r-Obs'd / $q_e t_r$	I	K_s	n	V_d	$\frac{q_a}{i-f}$	Mass erosion Inches depth
(1)	(2)	(3)	(4)	…)	(35)	(36)	(37)	(38)	(39)	(40)	(41)	(42)	(43)
Nov.30,1938	5	1	19	…9	.844	.0811	.481	1.16	41	0.2090	.0099	1.000	0.0032
Dec.1,1938	5	1	20	…5	1.253	.1748	.258	0.67	85	.1740	.0106	.996	.0043
" "	5	2	21	…5	1.298	.1110	.315	1.16	69	.1200	.0031	1.010	.0030
" 2 "	5	2	22	…4	1.645	.2040	.216	0.88	1080	.0101	.0064	.996	.0103
" 5 "	6	1	23	…9	.810	.0406	.468	1.01	296	.0427	.0053	1.021	.0065
" 6 "	6	1	24	…8	.942	.1118	.340	0.65	925	.0213	.0074	1.012	.0187
" 6 "	6	2	25	…4	1.105	.0827	.412	1.35	31	.2[illegible]90	.0160	1.000	.0120
" 7 "	6	2	26	…5	1.220	.1505	.233	0.75	67	.2500	.0105	1.016	.0210
" 7 "	7	1	27	…2	1.840	.0818	.272	1.50	36	.2900	.0029	1.033	.0060
" 8 "	7	1	28	…6	1.430	.1580	.291	1.20	84	.1560	.0118	.984	.0177
" 8 "	7	2	29	…7	2.110	.0603	.282	0.51	12	5.2400	.0006	1.012	.0060
" 9 "	7	2	30	…3	1.164	.1048	.315	1.29	78	.1560	.0081	.982	.0095
Feb.21,1939	10	1	48	…1	1.340	.1912	.267	0.90	400	.0166	.0028	1.014	.0168
" 23 "	10	1	49	…5	1.430	.1981	.227	0.69	1240	.0696	.0033	1.018	.0217
" 23 "	10	2	50	…3	1.750	.1269	.260	1.36	72	.0613	.0039	1.025	.0220
" 25 "	10	2	52	…7	1.340	.1455	.254	0.80	367	.0205	.0203	1.01[illegible]	.0275
Mar.14,1939	11	1	54	…5	1.600	.1123	.312	1.50	55	.0757	.0010	1.[illegible]	.0168
" 15 "	11	2	56	…2	1.470	.103[illegible]	.310	1.35	60	.0769	.0040	1.009	.0322
" 20 "	12	1	58	…0	.977	.1[illegible]	.315	0.[illegible]	482	.0184	.0252	1.000	.0266
" 21 "	12	2	60	…2	.323	.1170	1.043	0.76	5[illegible]0	.0122	.0049	1.003	.0348
" 24 "	13	1	64	…3	1.360	.2090	.301	1.16	13	.2540	.0004	1.008	.0308
" 24 "	13	2	65	…6	1.220	.1[illegible]50	.303	0.97	123	.0319	.0017	1.009	.0230
" 25 "	13	2	66	…0	1.810	.2910	.240	1.26	189	.0157	.0000	1.010	.0239
" 27 "	14	1	67	…4	.817	.0543	.627	1.54	26	.1220	.0021	1.019	.0078
" 28 "	14	1	68	…0	.884	.1042	.384	0.79	623	.0099	.0012	1.013	.0050
" 28 "	14	2	69	…5	1.090	.0415	.361	1.09	110	.0407	.0028	1.020	.0063
" 29 "	14	2	70	…5	1.320	.13[illegible]2	.340	1.34	4	.9120	.0019	1.036	.0021
Apr.5, "	15	1	71	…9	2.120	.2550	.192	1.16	12	.3520	.0007	1.020	.0400
" 6 "	15	1	72	…0	1.830	.2470	.202	0.98	36	.1390	.0008	1.020	.0335
" 11 "	15	3	74	…9	1.660	.2080	.236	1.09	25	.1300	.0009	1.016	.0405
" 12 "	15	3	76	…8	1.765	.2250	.213	1.00	27	.1800	.0016	1.012	.0335
" 12 "	16	1	77	…5	.795	.0562	.445	0.88	258	.0318	.0033	.987	.0054
" 19 "	16	1	78	…6	.695	.1103	.417	0.41	910	.0193	.0058	1.004	.0046
" 15 "	16	2	79	…9	.758	.0728	.398	0.52	240	.0576	.0096	.993	.0048
" 17 "	16	2	80	…4	.328	.1190	.370	0.56	197	.0653	.0123	1.000	.0062
" 7 "	18	1	89	…2	.890	.0878	.365	0.68	477	.0239	.0084	1.005	.0255
" 8 "	18	1	90	…2	.676	.1130	.372	0.70	611	.0181	.0110	1.000	.0196
" 13 "	19	1	94	…4	.825	.0848	.401	0.71	551	.0173	.0125	.879	.0120
" 14 "	19	1	95	…4	.778	.1528	.354	0.26	1032	.0241	.0039	1.000	.0045
July11 "	20	1	99	…9	.767	.0697	.416	0.67	121	.0115	.0109	.987	.0070
" 12 "	20	1	100	…8	.780	.1022	.372	0.41	282	.0081	.0191	..989	.0063
" 19 "	20	5	107	…7	.710	.0916	.404	0.39	346	.0689	.0159	.993	.0044
" 20 "	20	5	108	…0	.675	.1231	.406	0.26	310	.1152	.0249	.994	.0037
" 18 "	20	4	105	…4	.713	.0860	.396	0.34	908	.0307	.0073	1.011	.0098
" 19 "	20	4	106	…3	.970	.1465	.294	0.37	1211	.0212	.0081	.991	.0070
" 31 "	21	1	110	…0	.368	.0817	.367	0.65	380	.0278	.0129	1.005	
Aug.1 "	21	1	111	…5	.958	.1041	.336	0.68	363	.0278	.0290	.983	.0160
" 1 "	21	2	112	…4	.960	.0952	.357	0.81	134	.0618	.0221	.990	.0224
" 2 "	21	2	113	…8	.963	.1445	.333	0.66	442	.0230	.0832	1.000	.0125

TABLE 2 - SUMMARY OF SPRINKLED PLAT EXPERIMENTS - TUCSON ARIZONA

Date	Site No.	Plat No.	Run No.	Slope Percent	Initial Moisture Percent 0-2"	Initial Moisture Percent 0-6"	Moisture Equivalent	Initial Temperature Air °F	Initial Temperature Soil °F	Initial Temperature Water °F	Average Intensity i.p.h.	Duration t Minutes	Total P Inches	Total Q_s Inches	f_a	f_o	f_c	t_c	k_f	to hrs.	t_1 hrs.	t_n hrs.	t_r hrs.	t_{cr} hrs.	t_d hrs.	t_s hrs.	P_n In.	M	K_a	q_e i.p.h.	$\frac{1}{M+1}$	Q- calc.	Q_r Observ. In.	Ratio $\frac{Q_r\text{-Calc.}}{Q_r\text{-Obs'd.}}$	$q_e t_r$	$\frac{Q_r\text{-Obs'd}}{q_e t_r}$	I	K_s	n	V_d	$\frac{q_e}{1-f}$	Mass erosion Inches depth
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(21)	(23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)	(37)	(38)	(39)	(40)	(41)	(42)	(43)
Nov.30,1938	5	1	19	5.48		2.2	14.8	63	60	58	3.08	30	1.540	0.825	1.520	4.200	0.95	0.533	17.00	.0500	0.4200	.4500	.0381	.2830	.0267	.2500	1.386	1.45	88	2.13	.408	.0329	.039	.844	.0811	.481	1.16	41	0.2090	.0099	1.000	0.0032
Dec.1,1938	5	1	20	5.48	Near Moisture Equivalent		14.8	71	57	54	3.11	30	1.555	1.187	0.750	6.420	0.48	.170	40.90	.0333	.0200	.4667	.0667	.1170	.0133	.1000	1.451	2.10	192	2.62	.323	.0564	.045	1.253	.1748	.258	0.67	85	.1740	.0106	.996	.0043
" "	5	2	21	5.12		2.8	14.8	67	70	56	3.08	30	1.540	0.833	1.520	4.010	0.88	.415	10.70	.0500	.0330	.4488	.0500	.3670	.0167	.4000	1.382	1.45	148	2.22	.408	.0454	.035	1.298	.1110	.315	1.16	69	.1200	.0031	1.010	.0030
" 2 "	5	2	22	5.12	Near Moisture Equivalent		14.8	60	54	56	3.09	30	1.545	1.215	0.620	5.400	0.36	.150	30.40	0.333	.0190	.4667	.0750	.1500	.0142	.4000	1.442	1.82	2400	2.72	.355	.0724	.044	1.645	.2040	.216	0.88	1080	.0101	.0064	.996	.0103
" 5 "	6	1	23	9.06		2.8	14.8	62	52	56	3.10	30	1.550	0.521	2.350	4.100	1.67	.533	11.60	.0716	.0467	.4279	.0278	.3100	.0266	.3820	1.326	1.65	650	1.46	.378	.0154	.019	.810	.0406	.468	1.01	296	.0427	.0053	1.021	.0065
" 6 "	6	1	24	9.06	Near Moisture Equivalent		14.8	67	52	56	3.14	30	1.570	1.050	1.090	5.940	0.80	.183	39.40	.0367	.0208	.4639	.0472	.1500	.0158	.2160	1.457	2.13	2100	2.37	.320	.0358	.138	.942	.1118	.340	0.65	925	.0213	.0074	1.012	.0187
" 6 "	6	2	25	8.75		2.8	14.8	72	83	60	3.08	30	1.540	0.742	1.760	4.010	1.16	.403	16.60	.0600	.0234	.4403	.0431	.2560	.0367	.2920	1.346	1.20	64	1.92	.454	.0376	.034	1.105	.0827	.412	1.35	31	.2590	.0160	1.000	.0120
" 7 "	6	2	26	8.75	Near Moisture Equivalent		14.8	70	52	58	3.10	31	1.610	1.155	0.930	5.360	0.62	.190	36.70	.0375	.0200	.4792	.0597	.1170	.0175	.1000	1.486	2.00	150	2.52	.284	.0427	.035	1.220	.1505	.233	0.75	67	.2500	.0105	1.016	.0210
" 7 "	7	1	27	13.70		2.8	14.8	69	78	59	3.04	30	1.520	0.792	1.248	5.360	1.20	.300	28.80	.0481	.0375	.4519	.0431	.2520	.0106	.3670	1.374	1.00	72	1.90	.500	.0409	.022	1.840	.0818	.272	1.50	36	.2900	.0029	1.033	.0060
" 8 "	7	1	28	13.70	Near Moisture Equivalent		14.8	67	68	56	3.04	30	1.540	1.196	.422	4.000	.50	.150	33.00	.0291	.0083	.4709	.0633	.1210	.0208	.1670	1.403	1.40	180	2.50	.417	.0659	.046	1.430	.1580	.291	1.20	84	.1560	.0118	.984	.0177
" 8 "	7	2	29	13.70		2.8	14.8	73	68	59	3.06	30	1.530	0.525	1.815	4.210	1.53	.416	9.60	.0583	.0500	.4417	.0389	.3580	.0085	.4170	1.349	0.68	23	1.55	.595	.0359	.017	2.110	.0603	.282	0.51	12	5.2400	.0006	1.012	.0060
" 9 "	7	2	30	13.70	Near Moisture Equivalent		14.8	59	54	54	3.06	30	1.530	0.990	.921	3.385	.80	.250	17.40	.0301	.0083	.4699	.0472	.2200	.0218	.2420	1.437	1.72	220	2.22	.367	.0384	.033	1.164	.1048	.315	1.29	78	.1560	.0081	.982	.0095
Feb.21,193	10	1	48	1.98		2.8	27.5	62	48	56	3.33	30	1.665	1.220	.677	7.200	.50	.333	31.50	.0347	.0250	.4653	.0667	.2980	.0097	.3330	1.550	1.80	890	2.87	.357	.0683	.051	1.340	.1912	.267	0.90	400	.0166	.0028	1.014	.0168
" 23 "	10	1	49	1.98	Near Moisture Equivalent		27.5	70	54	54	3.30	30	1.650	1.230	.653	8.140	.44	.250	45.40	.0291	.0208	.4709	.0681	.2210	.0083	.2671	1.552	2.08	2800	2.91	.324	.0642	.045	1.430	.1981	.227	0.69	1240	.0696	.0033	1.018	.0217
" 23 "	10	2	50	2.00		2.8	27.5	75	70	60	3.30	30	1.650	1.124	.841	14.75	.75	.225	46.00	.0430	.0333	.4570	.0486	.1820	.0097	.2338	1.521	1.19	150	2.61	.457	.0579	.033	1.750	.1269	.260	1.36	72	.0613	.0039	1.025	.0220
" 25 "	10	2	52	2.00	Near Moisture Equivalent		27.5	51	44	52	3.30	30	1.650	1.312	.530	3.340	.43	.150	44.10	.0222	.0008	.4778	.0500	.1280	.0214	.1835	1.574	1.93	820	2.91	.341	.0496	.037	1.340	.1455	.254	0.80	367	.0205	.0203	1.014	.0275
Mar.14,193	11	1	54	2.16		4.0	19.2	80	73	68	3.26	60	3.260	1.975	1.150	6.580	.88	.625	12.60	.0722	.0666	.9278	.0472	.5530	.0056	.6000	3.061	1.00	112	2.38	.500	.0561	.035	1.600	.1123	.312	1.50	55	.0757	.0010	1.000	.0168
" 15 "	11	2	56	2.14		4.0	19.2	78	69	68	3.24	60	3.240	2.018	1.041	4.000	.78	.750	9.70	.0750	.0542	.9250	.0417	.6750	.0208	.6000	2.997	1.20	125	2.48	.454	.0468	.032	1.470	.1034	.310	1.35	60	.0769	.0040	1.009	.0322
" 20 "	12	1	58	1.36		4.8	16.8	86	87	68	3.26	60	3.260	2.134	.915	4.660	.72	.600	12.20	.0833	.0359	.9167	.0500	.5170	.0475	.6667	2.993	2.25	1100	2.54	.308	.0391	.040	.977	.1270	.315	0.56	482	.0184	.0252	1.000	.0266
" 21 "	12	2	60	1.36		4.8	16.8	78	77	69	3.26	60	3.260	2.180	.926	5.790	.79	.800	17.20	.0680	.0533	.9320	.0472	.7320	.0147	.6000	3.059	1.98	1300	2.48	.355	.0394	.122	.323	.1170	1.043	0.76	580	.0122	.0049	1.003	.0348
" 24 "	13	1	64	0.80	(0-3") 20.8	21.0	21.0	60	62	58	3.20	45	2.400	1.918	.537	5.360	.36	.417	23.00	.0258	.0250	.7242	.0731	.3910	.0008	.4333	2.319	1.45	29	2.86	.408	.0355	.063	1.360	.2090	.301	1.16	13	.2540	.0004	1.008	.0308
" 24 "	13	2	65	0.80	13.6	12.9	21.0	71	74	64	3.16	45	2.370	1.254	1.233	4.300	.60	.700	5.30	.0833	.0667	.6667	.0717	.6170	.0167	.6500	2.107	1.70	270	2.58	.371	.0685	.056	1.220	.1350	.303	0.97	123	.0319	.0017	1.009	.0230
" 25 "	13	2	66	0.80	(0-3") 20.8	21.0	21.0	75	61	64	3.20	45	2.400	1.890	.548	5.420	.32	.500	16.10	.0292	.0292	.7209	.1000	.4710		.3833	2.304	1.29	400	2.91	.437	.1270	.070	1.310	.2910	.240	1.26	189	.0157	.0000	1.010	.0239
" 27 "	14	1	67	1.32	(0-3") 6.6	6.0	16.3	70	70	66	3.70	60	3.700	1.028	2.250	52.100	2.10	.833	13.50	.2722	.2561	.7278	.0333	.5610	.0141	.4920	2.689	0.95	52	1.63	.512	.0278	.034	.817	.0543	.627	1.54	26	.1220	.0021	1.019	.0078
" 28 "	14	1	68	1.32	(0-1") 10.7	10.8	16.3	58	55	64	3.34	45	2.508	1.322	1.386	3.900	1.16	.584	12.20	.0625	.0542	.6875	.0472	.5220	.0083	.3920	2.297	1.95	1395	2.21	.339	.0354	.040	.884	.1042	.384	0.79	623	.0099	.0012	1.013	.0050
" 28 "	14	2	69	1.32	(0-3") 8.20	6.4	16.3	54	61	63	3.34	60	3.340	0.682	2.520	4.380	2.33	.718	5.10	.1472	.1415	.8628	.0403	.5710	.0057	.5167	2.879	1.55	240	1.03	.392	.0163	.015	1.090	.0415	.361	1.09	110	.0407	.0028	1.020	.0063
" 29 "	14	2	70	1.32	(0-1") 10.7	10.8	16.3	57	63	59	3.35	45	2.512	1.155	1.668	3.600	1.42	.412	7.00	.0361	.0167	.7139	.0661	.3760	.0194	.5167	2.382	1.22	8	2.00	.450	.0595	.015	1.320	.1322	.340	1.34	4	.9120	.0019	1.036	.0021
Apr.5, "	15	1	71	1.32		6.5	23.1	58	59	64	3.30	30	1.650	1.380	.381	10.500	.30	.158	52.00	.0236	.0208	.4764	.0833	.1340	.0028	.1415	1.571	1.45	26	3.06	.048	.1040	.049	2.120	.2550	.192	1.16	12	.3520	.0007	1.020	.0400
" 6 "	15	1	72	1.32			23.1	78	68	60	3.30	30	1.650	1.405	.311	12.300	.20	.175	44.30	.0236	.0208	.4764	.0781	.1510	.0028	.1250	1.571	1.70	80	3.16	.370	.0914	.050	1.830	.2470	.202	0.98	36	.1390	.0008	1.020	.0335
" 11 "	15	3	74	1.34		6.5	23.1	74	72	62	3.34	30	1.670	1.413	.352	6.260	.26	.184	34.50	.0250	.0208	.4750	.0664	.1590	.0042	.1425	1.588	1.55	54	3.13	.392	.0815	.049	1.660	.2080	.236	1.09	25	.1800	.0009	1.016	.0405
" 12 "	15	3	76	1.30		5.6	23.1	67	69	75	3.35	27	1.549	1.334	.171	5.580	.15	.250	36.50	.0250	.0208	.4375	.0694	.2250	.0012	.0917	1.413	1.66	60	3.24	.376	.0846	.048	1.765	.2250	.213	1.00	27	.1800	.0016	1.012	.0335
" 12 "	16	1	77	2.88		0.9	12.0	70	84	68	3.35	45	2.513	0.871	2.320	4.080	1.83	.568	10.60	.0583	.0375	.6917	.0375	.3417	.0208	.4420	2.318	1.82	570	1.50	.354	.0199	.025	.795	.0562	.445	0.88	258	.0318	.0033	.987	.0054
" 19 "	16	1	78	2.88		5.2	12.0	58	62	62	3.36	45	2.520	1.579	1.310	5.800	.90	.375	19.20	.0533	.0367	.6967	.0447	.2640	.0167	.2500	2.341	2.45	2100	2.47	.290	.0320	.046	.695	.1103	.417	0.41	910	.0193	.0058	1.004	.0046
" 15 "	16	2	79	2.86		0.9	12.0	44	59	56	3.38	45	2.540	0.986	2.230	5.400	1.73	.384	17.10	.0750	.0466	.6750	.0444	.2080	.0283	.1750	2.290	2.30	550	1.64	.303	.0220	.029	.758	.0728	.398	0.52	240	.0576	.0096	.993	.0048
" 17 "	16	2	80	2.86		5.2	12.0	64	68	63	3.34	45	2.505	1.231	1.770	7.700	1.20	.400	17.50	.0916	.0625	.6580	.0555	.2165	.0292	.1830	2.198	2.25	450	2.14	.307	.0365	.044	.828	.1190	.370	0.56	197	.0653	.0123	1.000	.0062
" 7 "	18	1	89	3.32	0.4	0.9	16.4	82	86	76	3.14	60	3.140	1.728	1.500	4.220	.97	.784	9.35	.0750	.0450	.9250	.0403	.3420	.0300	.4170	2.905	2.09	1080	2.18	.324	.0284	[illegible]	.830	.0878	.365	0.68	477	.0239	.0084	1.005	.0255
" 8 "	18	1	90	3.32	11.9	11.6	16.4	86	72	76	3.33	60	3.330	2.455	.890	5.490	.69	.233	29.20	.0400	.0208	.9590	.0428	.1600	.0192	.2660	3.193	2.07	1380	2.64	.326	.0368	.042	.676	.1130	.372	0.70	611	.0181	.0110	1.000	.0196
" 13 "	19	1	94	2.33	1.7	2.5	16.0	100	106	85	3.00	44	2.238	1.295	1.370	4.270	.87	.540	11.60	.0667	.0417	.6830	.0458	.3080	.0250	.4330	2.049	2.05	1200	1.87	.328	.0280	.034	.825	.0848	.401	0.71	531	.0173	.0125	.879	.0120
" 14 "	19	1	95	2.33	9.9	9.1	16.0	89	78	78	3.12	45	2.340	1.688	.870	5.570	.62	.280	23.30	.0417	.0292	.7080	.0614	.2080	.0125	.2250	2.209	2.65	2400	2.50	.274	.0420	.054	.778	.1528	.354	0.26	1032	.0241	.0039	1.000	.0045
July11 "	20	1	99	4.84	0.5	0.6	13.7	96	106	86	3.15	45	2.362	0.968	2.060	8.870	1.57	.300	24.20	.0917	.0615	.6580	.0444	.1750	.0292	.2420	2.073	2.11	275	1.56	.321	.0220	.029	.767	.0697	.416	0.67	121	.0115	.0109	.987	.0070
" 12 "	20	1	100	4.84	5.4	9.8	13.7	88	82	84	3.04	45	2.280	1.200	1.550	7.170	1.18	.270	26.40	.0791	.0450	.6700	.0555	.1710	.0342	.1290	2.037	2.45	650	1.84	.290	.0300	.038	.780	.1022	.372	0.41	282	.0081	.0191	.989	.0063
" 19 "	20	5	107	4.80	3.8	4.0	13.7	94	105	84	3.11	45	2.332	1.030	1.860	9.840	1.53	.216	34.40	.0783	.0483	.6710	.0583	.1220	.0300	.1540	2.087	2.48	800	1.57	.287	.0260	.037	.710	.0916	.404	0.39	346	.0689	.0159	.994	.0044
" 20 "	20	5	108	4.80	10.3	9.8	13.7	88	84	80	3.15	45	2.362	1.329	1.520	7.510	1.17	.240	30.40	.0750	.0377	.6750	.0625	.1330	.0374	.1330	2.126	2.65	720	1.97	.274	.0340	.050	.675	.1231	.406	0.26	310	.1152	.0249	.994	.0037
" 18 "	20	4	105	5.00	2.6	2.6	13.7	94	100	80	3.15	45	2.362	1.061	1.860	9.650	1.45	.275	25.60	.0833	.0624	.6670	.0500	.1667	.0208	.1000	2.101	2.55	2100	1.72	.282	.0240	.034	.713	.0860	.396	0.34	908	.0307	.0073	1.011	.0098
" 19 "	20	4	106	5.00	10.4	11.1	13.7	89	87	82	3.20	45	2.400	1.564	1.130	5.080	.88	.284	24.40	.0433	.0250	.7070	.0639	.2000	.0183	.1500	2.262	2.50	2800	2.29	.286	.0420	.043	.970	.1465	.294	0.37	1211	.0212	.0081	.991	.0070
" 31 "	21	1	110	2.60	1.7	2.4	12.1	92	103	80	3.12	60	3.120	1.747	1.450	6.570	1.17	.280	25.60	.0667	.0392	.9330	.0417	.1670	.0267	.1670	2.911	2.13	660	1.96	.319	.0260	.030	.868	.0817	.161	[illegible]	380	.0278	.0129	1.005	
Aug.. "	21	1	111	2.60	11.2	10.9	12.1	89	82	78	3.10	60	3.100	2.193	.920	6.570	.79	.150	48.70	.0400	.0200	.9600	.0458	.0933	.0200	.0780	2.976	2.10	620	2.27	.322	.0340	.035	.958	.1041	.336	0.68	363	.0278	.0290	.983	.0160
" 1 "	21	2	112	2.50	1.7	2.4	12.1	95	102	80	3.10	60	3.100	1.672	1.400	6.990	1.12	.270	26.10	.0650	.0417	.9350	.0486	.1670	.0233	.1830	2.898	1.92	300	1.96	.343	.0330	[illegible]	.960	.0952	.357	0.81	134	.0618	.0221	.990	.0224
" 2 "	21	2	113	2.50	9.9	10.0	12.1	83	85	76	3.10	60	3.100	2.348	.760	7.020	.62	.162	42.80	.0367	.0208	[illegible]	.0583	.1167	.1585	.1000	2.982	2.12	1000	2.48	.320	.0460	.048	.963	.1445	.333	0.66	442	.0230	.0832	1.000	.0125

Col. 13, t, duration of application of water, in minutes.

Col. 14, P, total rainfall or water applied, in inches.

Col. 15, Q_s, total run-off in inches depth on plat area, as measured.

Col. 16, f_a, average infiltration-capacity from beginning to end of run-off, inches per hour, given by the equation $f_a = \frac{P_n - Q_s}{t_n - \frac{t_r}{3}}$. For meanings of P_n, t_n, and t_r, see notes for columns 28, 23, 24, respectively.

Col. 17, f_0, initial infiltration-capacity at beginning of rain or application of water, inches per hour, determined as subsequently described.

Col. 18, f_c, final constant or surface minimum infiltration-capacity, inches per hour, determined as subsequently described from the infiltration-capacity curve.

Col. 19, t_c, time in hours from beginning of rain or application of water at which infiltration-capacity becomes sensibly constant.

Col. 20, K_f, exponential constant in infiltration-capacity equation, determined as subsequently described.

Col. 21, t_0, time from beginning of application of water to beginning of run-off, hours, determined directly from hydrograph.

Col. 22, t_1, initial interval, if any, in hours, during which infiltration-capacity exceeds rain intensity. Then $t_0 = t_1 + t_d$ (see Col. 26).

Col. 23, t_n, net time from beginning of run-off to end of rainfall excess, hours, from hydrograph; $t_n = t - t_0$.

Col. 24, t_r, duration of residual run-off, hours, from hydrograph.

Col. 25, t_{cr}, the critical time or time, in hours, from beginning of run-off at which the infiltration-capacity becomes constant, derived from infiltration-capacity curve after this had been determined.

Col. 26, t_d, initial time required to fill depression storage, hours; determined from hydrograph and infiltration-capacity curve. The time interval t_d begins when the infiltration-capacity drops down to equality with the rain intensity, and ends when surface run-off begins. It is determined from the hydrograph and infiltration-capacity curves. $t_d = t_0 - t_1$.

Col. 27, t_s, time, in hours, from beginning of surface run-off at which surface detention and surface run-off become sensibly constant. This is related to the critical time or concentration interval of the so-called rational theory of surface run-off.

Col. 28, P_n, total precipitation or water applied from beginning of run-off to end of rainfall excess, inches. Determined from mass rainfall diagram. For constant rainfall this equals i (Col. 15) times t_n (Col. 23).

Col. 29, M, the exponent, which is constant for a given experiment, in the surface run-off intensity equation $q_s = K_s \delta M$; determined from logarithmic platting of q_s in terms of δ a, where δ

is the depth, in inches, of surface detention along the outlet and of the plat, and δ_a is the average depth, in inches, of surface detention on the plat.

Col. 30, K_a, coefficient in the surface run-off equation, expressed in terms of average surface detention depth δ_a, including depression storage, or $q_s = K_a \delta_a M$. The value of K_a is determined directly from logarithmic platting of q_s in terms of δ_a for a value of $\delta_a = 1.0$.

Col. 31, q_e, run-off intensity at end of rainfall excess or at end of application of water, inches per hour; determined directly from hydrograph.

Col. 32, $\frac{1}{M + 1}$. This is the ratio, derived analytically, between the residual run-off and the residual run-off which would have occurred during the time t_r at the rate q_e. Since q_e and t_r can be determined from the hydrograph and M can also be determined, this ratio affords a means of estimating the residual run-off in cases where it has not been actually measured.

Col. 33, q_r, calculated, inches. This is a calculated value of the residual run-off after the end of rainfall excess, determined by multiplying together the quantities in Cols. 31, 32, and 24.

Col. 34, q_r, observed, inches. Residual run-off derived directly by measuring the area under the residual run-off curve on the hydrograph.

Col. 35 is the ratio of the observed residual run-off to the residual run-off calculated, as given in Col. 33. Owing to the practical difficulties of accurate determination of residual run-off from a small plat, there are considerable differences between the observed and calculated values in individual cases.

Col. 36, $q_e t_r$. Equals Col. 31 times Col. 24.

Col. 37 is the ratio of the observed residual run-off Q_r to the product $q_e t_r$. Analytical treatment of the subject indicates that this ratio should have a value $\frac{1}{M + 1}$, as given in Col. 32.

Col. 38, I, index of turbulence; given by the equation $I = \frac{3}{4}(3.0 - M)$. For fully turbulent flow M = 5.3 and I = 1.0. For laminar flow M = 3.0 and I = 0. The value of I is an indicator of the fraction of the total volume of surface run-off in which turbulence occurs. In most cases some of the flow, particularly thin films on slopes of tillage marks, or part of the flow through depressions, may be laminar, the remaining flow being generally turbulent.

Col. 39, K_s, coefficient of overland flow in terms of depth along outlet margin. The value of K_s can be derived from K_a (Col. 30) and M (Col. 29) by using the equation $K_s = \left(\frac{M}{M + 1}\right)^M K_a$. The coefficient K_s takes into account the effect of the principal variables - slope, roughness, index of turbulence and length of overland flow, in relation to surface run-off, and its value is expressed in terms of these variables by the general equation $K_s = 1020 \sqrt{\frac{S}{\ln l_0}}$, where l_0 is the length of overland flow, in feet.

This equation is not applicable if the flow is not more than one-third turbulent.

Col. 40, roughness coefficient, given by the equation $n = \frac{1020\sqrt{S}}{I K_s \tau_0}$, S being the absolute surface slope. The difference between slope of the water surface on the plat and the slope of the plat surface is usually so slight that the latter is used in the computations.

Col. 41, V_d, depression storage volume, inches depth; the area between the infiltration-capacity curve and a horizontal line corresponding to the rain intensity i during the time interval t_1, when f = i, and t_0, the time at which run-off begins. The value of V_d can be closely approximated by the equation $V_d = \left(\frac{i - f'}{2}\right) t_d$ where f' is the infiltration-capacity, in inches per hour, at the time of beginning of run-off, as derived from the infiltration-capacity curve.

Col. 42, $\frac{q_e}{i - f_c}$. This is the ratio of the maximum run-off intensity which, with constant rain intensity, occurs at the end of rainfall excess, to the constant supply rate σ after the infiltration-capacity has become constant. The two quantities q_e and $i - f_c$ should be sensibly equal, as they are, in fact, as shown by the data in Col. 42. This fact makes it possible to determine directly the maximum infiltration-capacity if f_c is known. As shown in another paper[1] the infiltration-capacity decreases with duration of application

[1]Horton, Robert E., op. cit. p. 1.

of rain in accordance with the equation $f = f_c + (f_0 - f_c)e^{-K_f t}$. The method of derivation of the constants f_0, f_c, and K_f in this equation, for a given run-off plat experiment, is fully described in the paper referred to.

The time t_c at which the infiltration-capacity becomes sensibly constant is taken as the time, derived from this equation, at which the infiltration-capacity falls to a value $1.01f_c$, and is computed as follows: $t_c = \left(\frac{1}{K_f}\right) \ln 100 \left(\frac{f_0 - f_c}{f_c}\right)$.

The critical time t_c required for the infiltration-capacity to reach its normal minimum value is an important characteristic of the soil and it is highly important in relation to surface run-off and erosion phenomena for the reason that for storms of less duration than t_c, the infiltration-capacity is always above its minimum value.

Col. 43, mass erosion expressed in inches depth of soil at volume weight removed during period of run-off.

<u>Determination of varying infiltration-capacities from run-off graph:</u>[1] Sample data and the computations of infiltration rate, f, from observed data are given in Table 3. Column (1) gives time increments at end of which Q was observed. Columns (2) and (3) give total rainfall and run-off, respectively, at the end of each time increment. Column (4) gives total run-off at the end of the given time increment plus the residual run-off which would have occurred

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[1]Horton, Robert E., <u>op. cit.</u> p. 1.

if rain had ended at end of the given time increment. Column (5) gives increment of run-off resulting from rain which fell in given time interval. This is the difference between Q_2 on a given line and that on the preceding line. Column (6) gives increment of rainfall. Column (7) is the increment of total infiltration, ΔF, for the time increment Δt_F, obtained by subtracting item in Column (5) from that in Column (6). This, in turn divided by the time increment, Δt_F, gives average infiltration rate f, Column (9), at midpoint of the given time increment.

TABLE 3.

Sample data and computation of infiltration rate from observed data.

Time	Rainfall	Run-off	Computations of f					Infiltration
t	P	Q	Q_2	ΔQ_2	ΔP	ΔF	Δt_F	f
Minutes	Inches	Inches	Inches	Inches	Inches	Inches	Hours	Inches per hour
1	2	3	4	5	6	7	8	9
0	0							Rain started
1.00	0.0555						0.0167	f=i = 3.33
2.42	.1343	0.0000						Run-off started
3.53								1.39
4.00	.2220	0.0196	0.0361	0.0361	0.0377	0.0511	.0368	
5.56								0.94
7.00	.3885	.1225	.1525	.1164	.1665	.0501	.0530	
8.50								0.80
10.00	.5550	.2401	.2768	.1243	.1665	.0422	.0503	
12.50								0.83
15.00	.8325	.4450	.4850	.2082	.2775	.0693	.0834	
22.50								0.72
30.00	1.665	1.0967	1.1382	.6532	.8325	.1793	.2502	
37.50								0.68
45.00	2.4975	1.7581	1.7998	.6616	.8325	.1709	.2502	
52.50								0.71
60.00	3.3300	2.4133	2.4550	.6552	.8325	.1773	.2500	App. stopped
62.57		2.4550						Run-off stopped

The curve corresponding to the value of "f" in Table 3 can be represented by a general equation of relation of infiltration-capacity to duration of rainfall of the form $f = f_c+(f_o - f_c)e - K_f t$. Sample determination of constants in infiltration-equation are given in Figure 8. The constants are substituted in the equation and values of f are computed as shown in Table 4.

TABLE 4 – Computed values: $f = f_c+(f_o - f_c)e - K_f t$ for Run 90
$f_c = 0.69$ and from Figure 7, $f_o = 5.49$ and $K_f = 29.20$

t Min.	t Hr.	$K_f t$	$e^{K_f t}$	$(f_o - f_c)e - K_f t$	f
1	0.0167	0.487	1.63	2.940	3.63
2	.0333	0.971	2.65	1.810	2.50
3	.0500	1.460	4.31	1.110	1.80
5	.0833	2.430	11.40	0.420	1.11
7	.1167	3.410	30.00	0.160	0.85
10	.1667	4.870	132.00	0.038	0.73
15	.2500	7.300	1500.00	0.003	0.69
20	.3333	9.720	16500.00	0.000	0.69

<u>Characteristics of hydrographs</u>: The hydrographs for a number of experiments are shown in Figures 9, 10, 11, 12, and 13. These hydrographs cover a variety of examples of different sites with different slopes, soils, and duration of experiments.

All of the infiltration curves have similar shapes, beginning with high values and declining rapidly for the first ten minutes after which they continue to decline slowly until a nearly constant rate of infiltration is reached. The run-off curves show distinct waviness in many instances, especially after the flow becomes stable. The presence or absence of waviness does not appear to be closely related to soil surface or cover conditions but there

t_1 = 0.025 hr. f_1 = 3.00 f_c = 0.69
t_2 = 0.117 hr. f_2 = 0.85

K_f	$.025K_f$	$e^{.025K_f}$	f_o-f_c
24	0.600	1.82	4.20
26	0.650	1.92	4.44
28	0.700	2.03	4.70
29	0.725	2.07	4.78
30	0.750	2.12	4.90
32	0.800	2.22	5.13
34	0.850	2.34	5.41

K_f	$.117K_f$	$e^{.117K_f}$	f_o-f_c
24	2.80	16.50	2.64
26	3.03	20.80	3.33
28	3.27	26.20	4.20
29	3.38	29.60	4.73
30	3.51	33.40	5.35
32	3.73	42.00	6.72
34	3.97	53.00	8.50

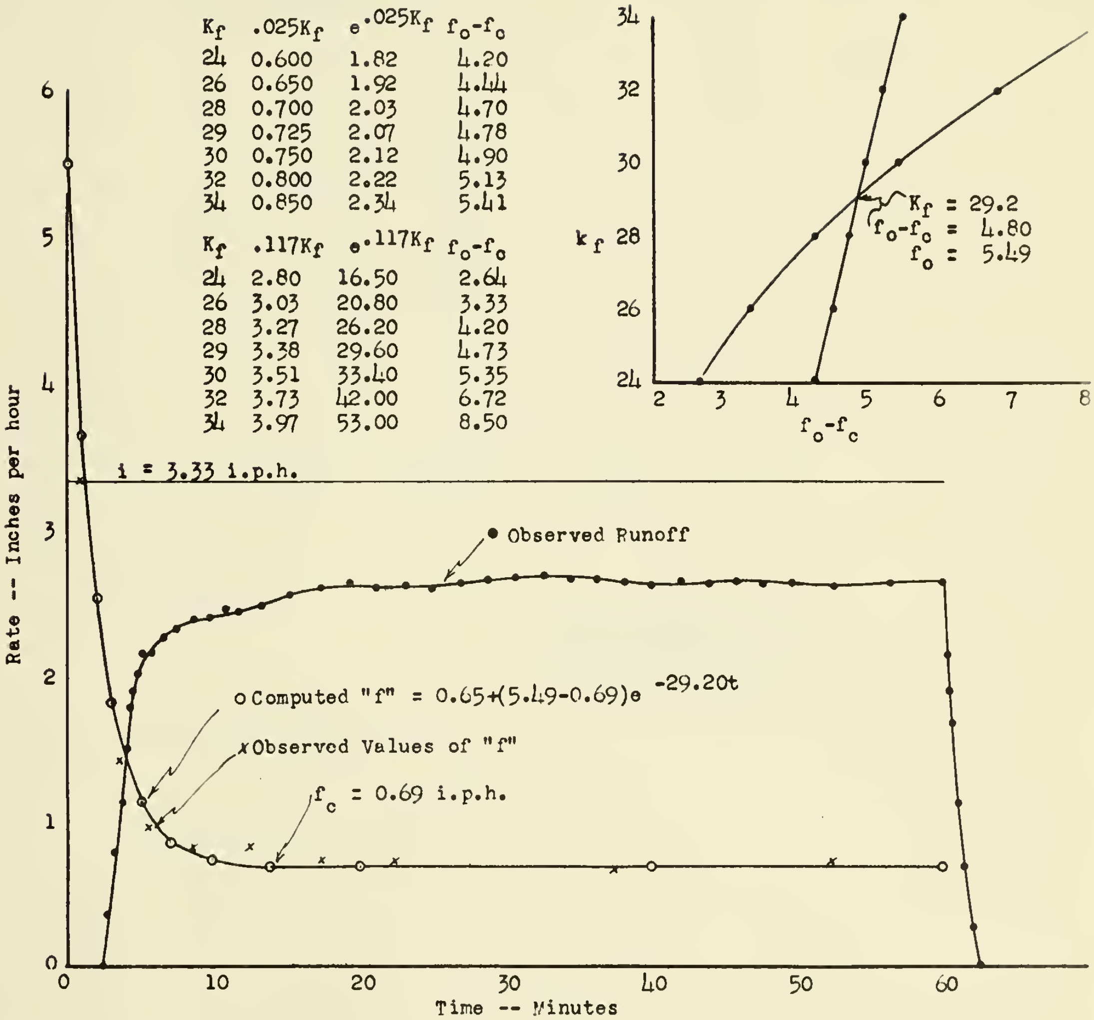


Figure 8.--Determination of Constants in Infiltration-equation. Run 90 Site 18.

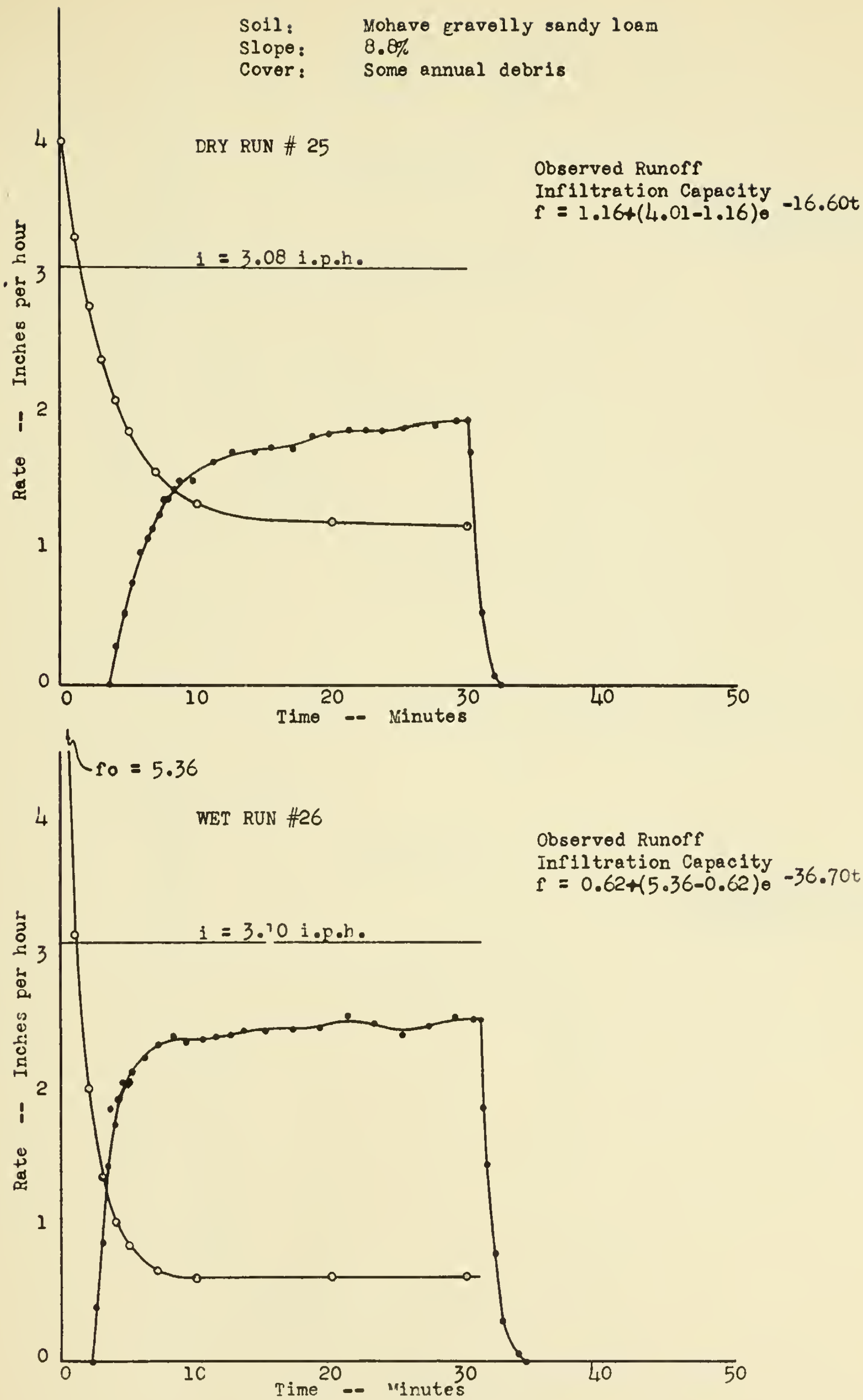


Figure 9.--Site 6 (Tripp Canyon) Plot 2.

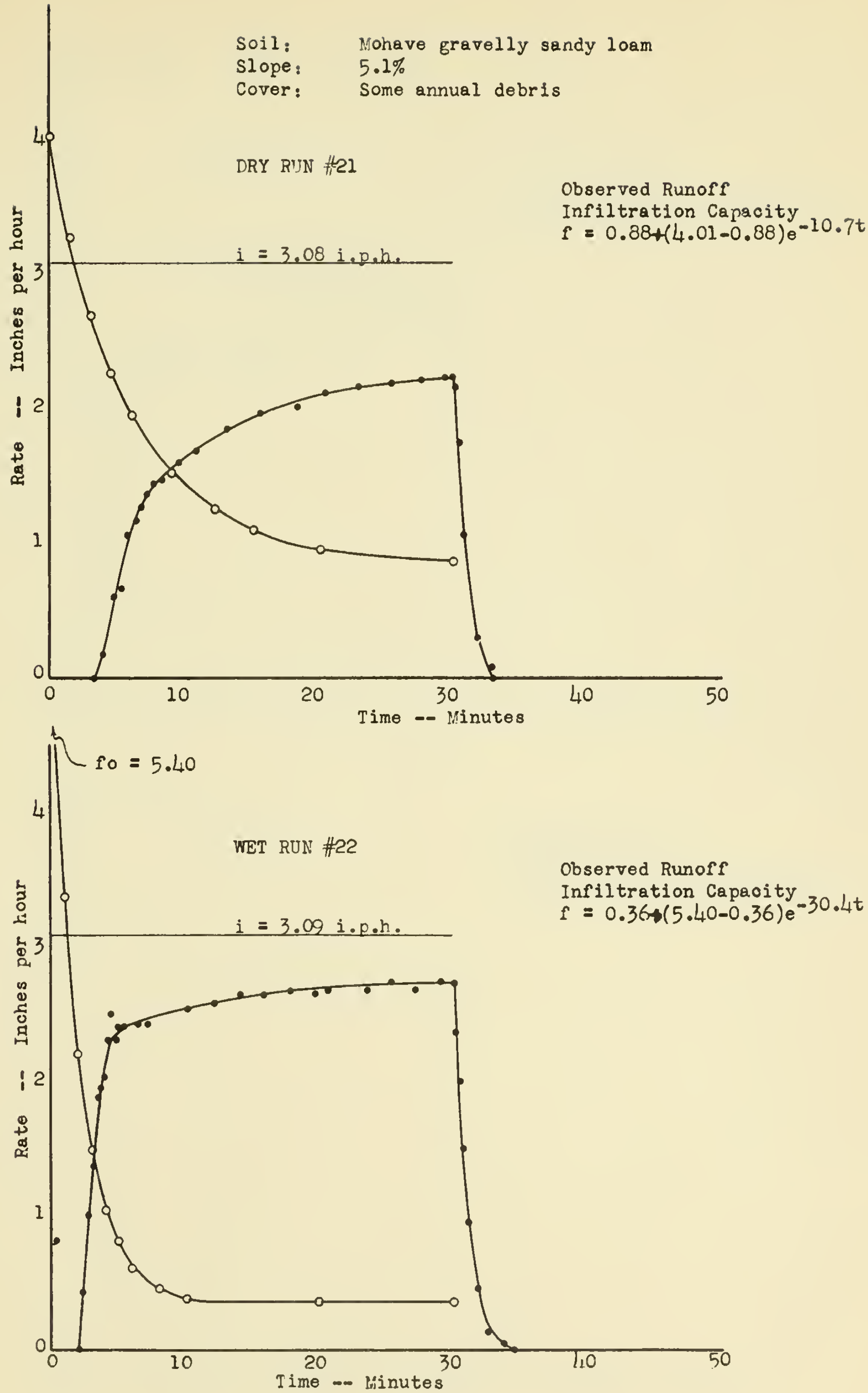


Figure 10.--Site 5 (Tripp Canyon) Plot 2.

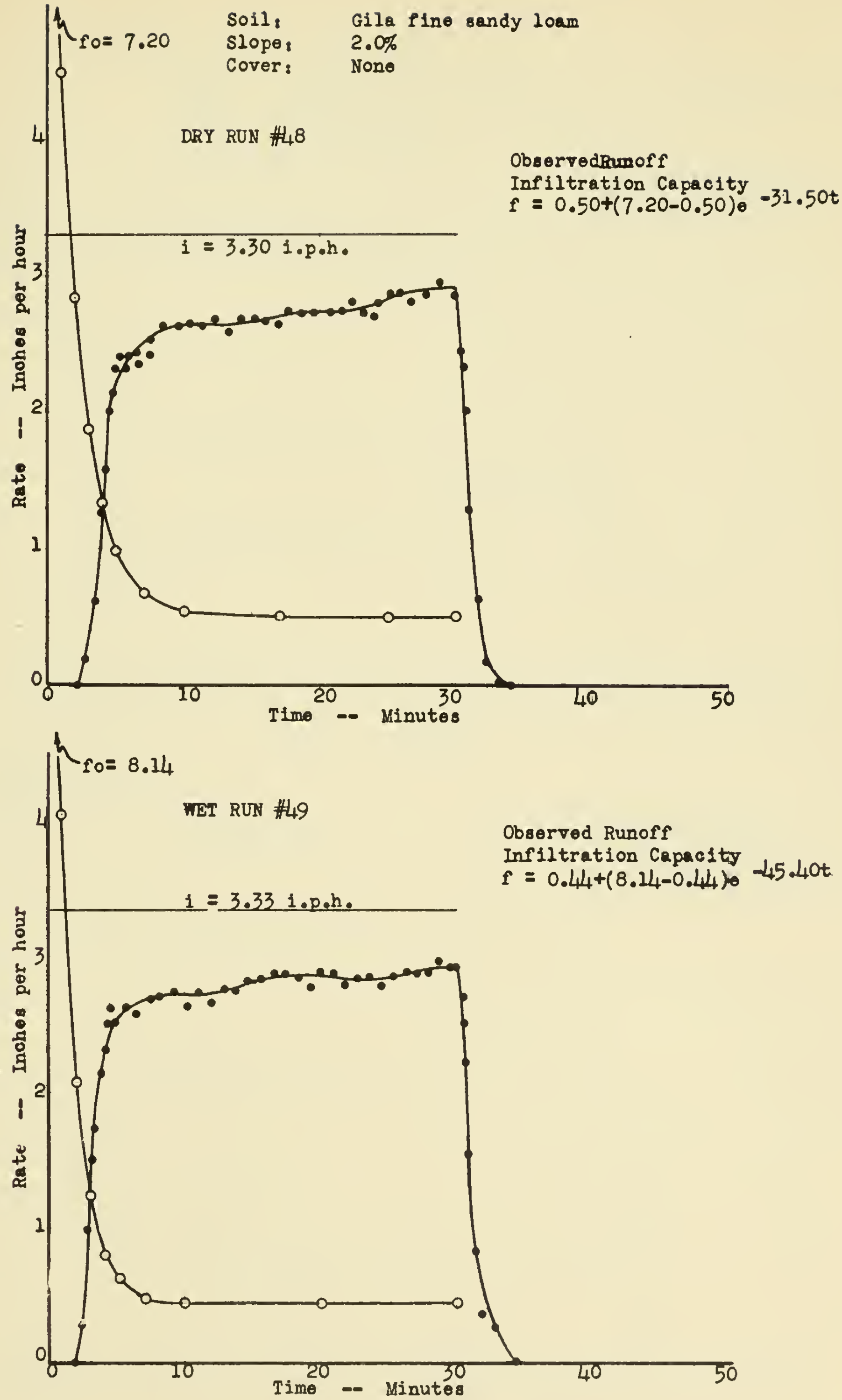


Figure 11.--Site 10 (City Farm) Plot 1.

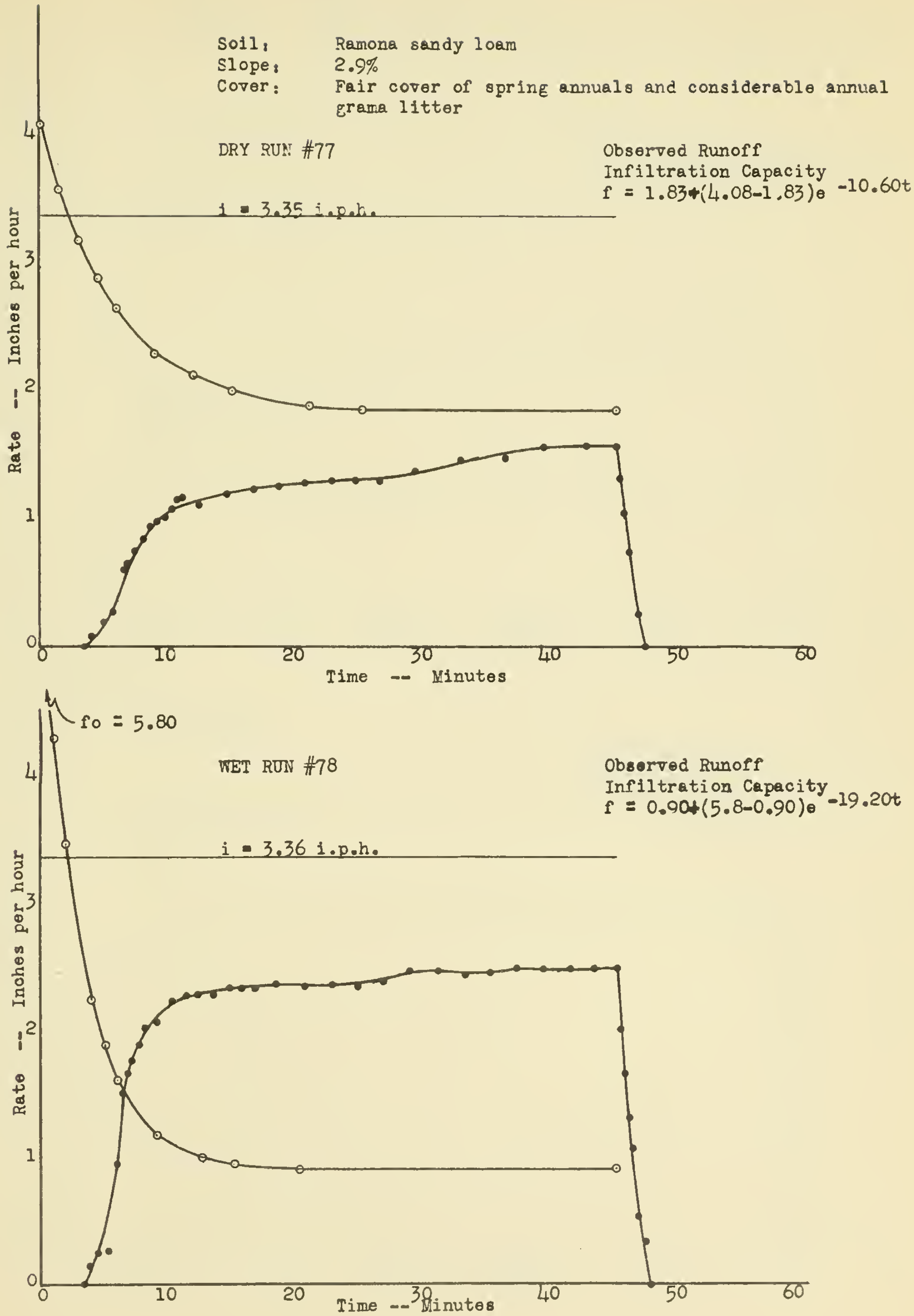
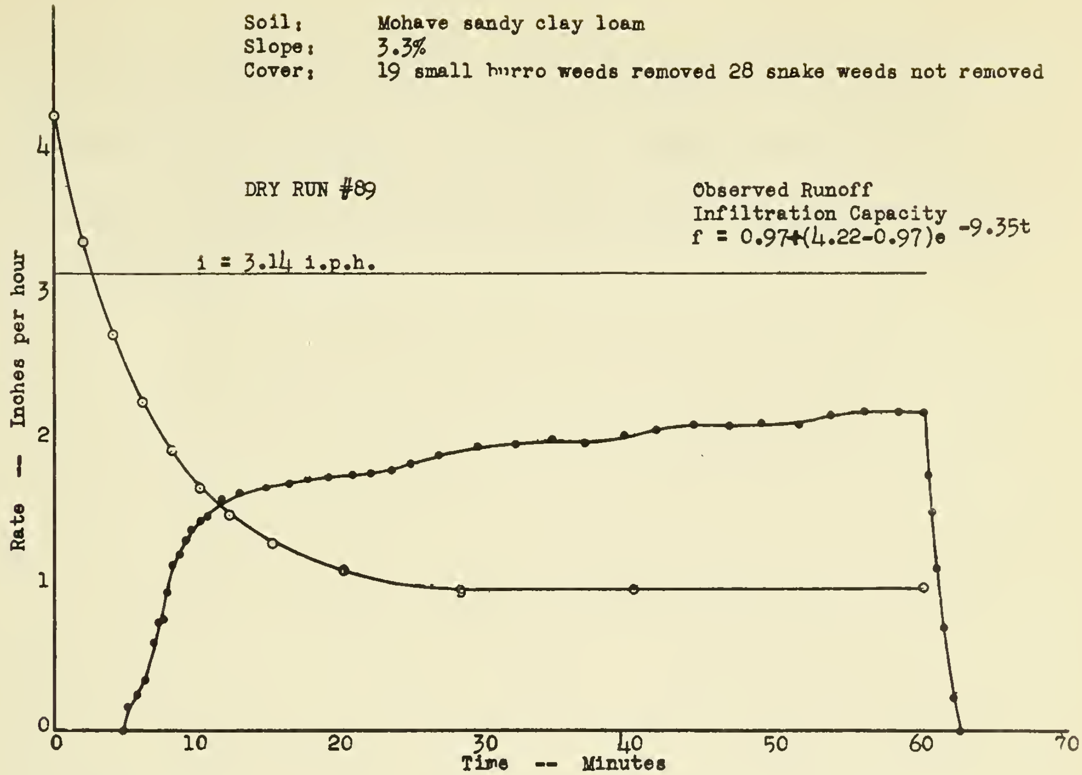


Figure 12.--Site 16 (Beach Ranch) Plot 1.



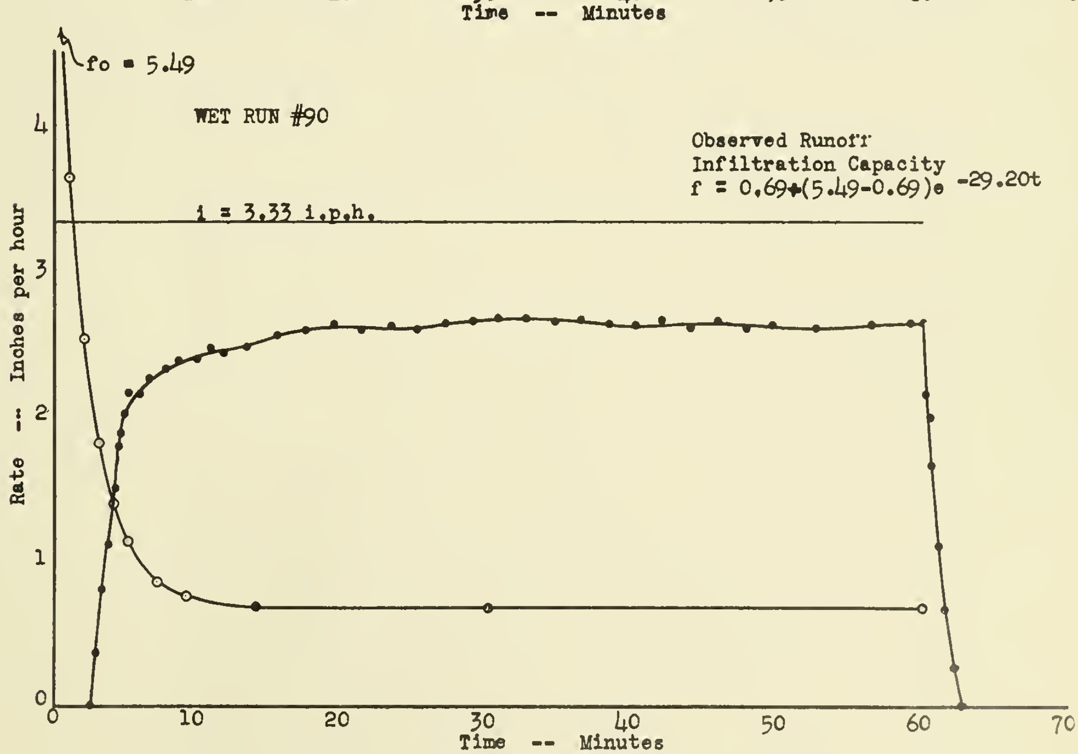


Figure 13.--Site 18 (Artesia) Plot 1.

is an indication though perhaps not significant of a relation to slope and erosion. The wave crests vary in time from 8 minutes on the steeper slopes to 13 minutes on the flatter slopes such as on sites 6 and 18.

TABLE 5. Averages by Sites

Site No.	Slope %	Dry Runs i	Dry Runs f_o	Dry Runs f_c	Dry Runs t_c hr.	Dry Runs M	Dry Runs I	Dry Runs K_f	Dry Runs K_a	Dry Runs K_s	Dry Runs n	Dry Runs Mass Erosion Inches	Wet Runs i	Wet Runs f_o	Wet Runs f_c	Wet Runs t_c	Wet Runs M	Wet Runs I	Wet Runs K_f	Wet Runs K_a	Wet Runs K_s	Wet Runs n	Wet Runs Mass Erosion Inches
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)	(23)	(24)
5	5.3	3.08	4.10	0.92	0.351	1.45	1.16	13.85	118	55	0.164	0.0031	3.10	5.91	0.42	0.160	1.96	0.78	35.65	1296	582	0.092	0.0073
6	8.9	3.09	4.06	1.42	.468	1.42	1.18	14.10	357	164	.171	.0092	3.12	5.65	0.71	.188	2.06	0.70	38.05	1125	496	.136	.0188
7	13.7	3.05	4.78	1.36	.358	0.84	1.00	19.20	48	24	.290	.0060	3.05	3.69	0.65	.200	1.56	1.24	25.20	200	81	.156	.0136
10	2.0	3.31	10.98	0.63	.279	1.50	1.13	38.80	520	236	.039	.0194	3.30	5.74	0.44	.200	2.00	0.74	44.80	1810	804	.045	.0246
11	2.1	3.25	5.29	0.83	.688	1.10	1.42	11.20	118	58	.076	.0088	- --	- --	- --	- No Data-		- --	-- --	----	---	----	----
12	1.4	3.26	5.22	0.75	.700	2.12	0.66	14.70	1200	531	.016	.0127	- --	- --	- --	- No Data-		- --	-- --	----	---	----	----
13.	0.8	3.20	4.30	0.60	.700	1.70	0.97	5.30	270	101	.032	.0118	3.16	5.39	0.34	.458	1.37	1.22	19.60	214	123	.016	.0158
14	1.3	3.34	*	2.22	.775	*	*	*	*	*	*	.0019	3.34	*	1.29	.498	*	*	*	*	*	*	.0025
15	1.3	3.32	8.38	0.28	.171	1.50	1.12	43.25	40	18	.266	.0402	3.32	8.94	0.18	.212	1.68	0.99	40.40	70	32	.160	.0336
16	2.9	3.36	4.47	1.78	.476	2.06	0.70	13.75	550	249	.043	.0039	3.35	6.75	1.05	.388	2.35	0.48	18.35	1275	554	.042	.0054
18	3.3	3.14	4.22	0.97	.784	2.09	0.68	9.35	1080	477	.024	.0150	3.33	5.49	0.69	.233	2.07	0.70	29.20	1380	611	.018	.0095
19	2.3	3.00	4.27	0.87	.540	2.05	0.71	11.60	1200	531	.017	.0083	3.12	5.57	0.62	.280	2.65	0.26	23.30	2400	1032	.024	.0029
20	4.9	3.14	9.52	1.52	.264	2.44	0.47	28.07	1588	458	.037	.0051	3.13	6.59	1.08	.265	2.52	0.35	27.07	2085	601	.048	.0037
21	2.6	3.11	6.78	1.15	.275	2.02	0.73	25.85	480	257	.045	.0100	3.10	6.80	0.70	.156	2.11	0.67	45.75	910	402	.025	.0075

* Data on the rising side of the hydrographs were not complete enough to solve for values of f_c, K_f, M, etc.

ANALYSIS OF EXPERIMENTS

Averages by sites and by runs: The averages for some of the principal factors derived from the experiments are shown in Table 5. Figure 14 shows locations of the sites where the different series of experiments were conducted.

Since, with a few exceptions, each site represents in general a different soil type and different cover condition, it is believed that averages of all the experiments at a given site will show, as far as the number of experiments performed are adequate, true differences due to soil and cover.

An experiment was counted as a dry run if it was the first or initial run on a plat made under existing conditions of field moisture which for most of the experiments were quite low, surface soils frequently being nearly in an air-dry condition. A run was designated as a wet run if it followed a dry run usually within 24 hours. In many cases the soils were nearly at field moisture capacity when the wet run was started.

It will be noted in Table 2 that there were marked differences in the value of the constant infiltration-capacity f_c for both the dry runs and the wet runs at the different sites. In general there was a different slope at each site, but since infiltration-capacity is but little affected by slope, as shown later, this does not account for the difference. Part of the

Figure 14. Location of sites.

difference is, however, due to seasonal variations as runs at different sites were made in different months. Aside from this it appears that the differences in f_c at the different sites are chiefly representative of soil and cover conditions though the latter factor is of lesser importance since the cover was very sparse on most of the sites studied.

With respect to run-off characteristics, the run-off exponent M is generally higher at a given site for wet than for dry runs, seeming to indicate a smoother surface. Indications are that values of the roughness factor n are generally lower for wet than for dry runs on a given site except where the soil surface is susceptible to severe checking and cracking between runs such as on sites 10 and 15. Increase of M and decrease of n both correspond to increased facility of run-off. Such differences between wet and dry runs have not heretofore been noticed and are probably due in this case to the effect of the initial wetting on the vegetal cover and on the soil surface itself.

Since most of the sites had little or no plant cover, the rate of erosion seems to be a function of other surface conditions such as soil puddling and erosion pavement. Presence of the latter appears to be responsible for low rates of erosion on sites 5, 6, 7, 16, 19, and 20. The effect of slope on erosion is not clearly shown in these experiments since the range of slopes is small except on sites 5, 6, and 7 where the erosion pavement prevented active soil removal.

Averages of the principal factors for dry and wet runs and for all runs are shown in Table 6.

TABLE 6. Averages of Runs

	No. of Runs	f_o	f_c	t_c	K_f	M	K_a	I	K_s	n	$\frac{q_e}{i-f_c}$	Mass Erosion Inches Depth
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Dry Runs	24	6.25	1.05	0.441	20.83	1.71	534	0.92	237	0.095	1.001	.0116
Wet Runs	21	6.12	0.64	.249	31.86	2.02	1036	.75	455	.076	1.001	.0133
Total Runs	45	6.19	0.86	.352	25.97	1.85	768	.84	339	.086	1.001	.0124

A slight reduction in initial infiltration-capacity f_o and a marked reduction in constant infiltration-capacity f_c from dry to wet runs are indicated. The time t_c required for infiltration capacity to become constant was less for the wet than for the dry runs. The infiltration capacity constant K_f showed a marked increase from dry to wet runs. The run-off exponent M showed an increase and the index of turbulence I showed a decrease from dry to wet runs. The run-off on the whole was almost fully turbulent. The roughness factor n shows a significant decrease from dry to wet runs. Column 11 has been included showing the ratio of run-off intensity to the constant supply rate $i-f_c$. q_e is the run-off intensity at the end of the application of water. This should be equal to the supply rate $i-f_c$ with constant infiltration-capacity. It will be noted that the experiments show the ratio of these quantities to be very close

to unity in all cases, as it should be in accordance with the infiltration theory of surface run-off.

The average infiltration-capacity curves derived from all of the experiments and for wet and dry runs, respectively, are shown in Figure 15.

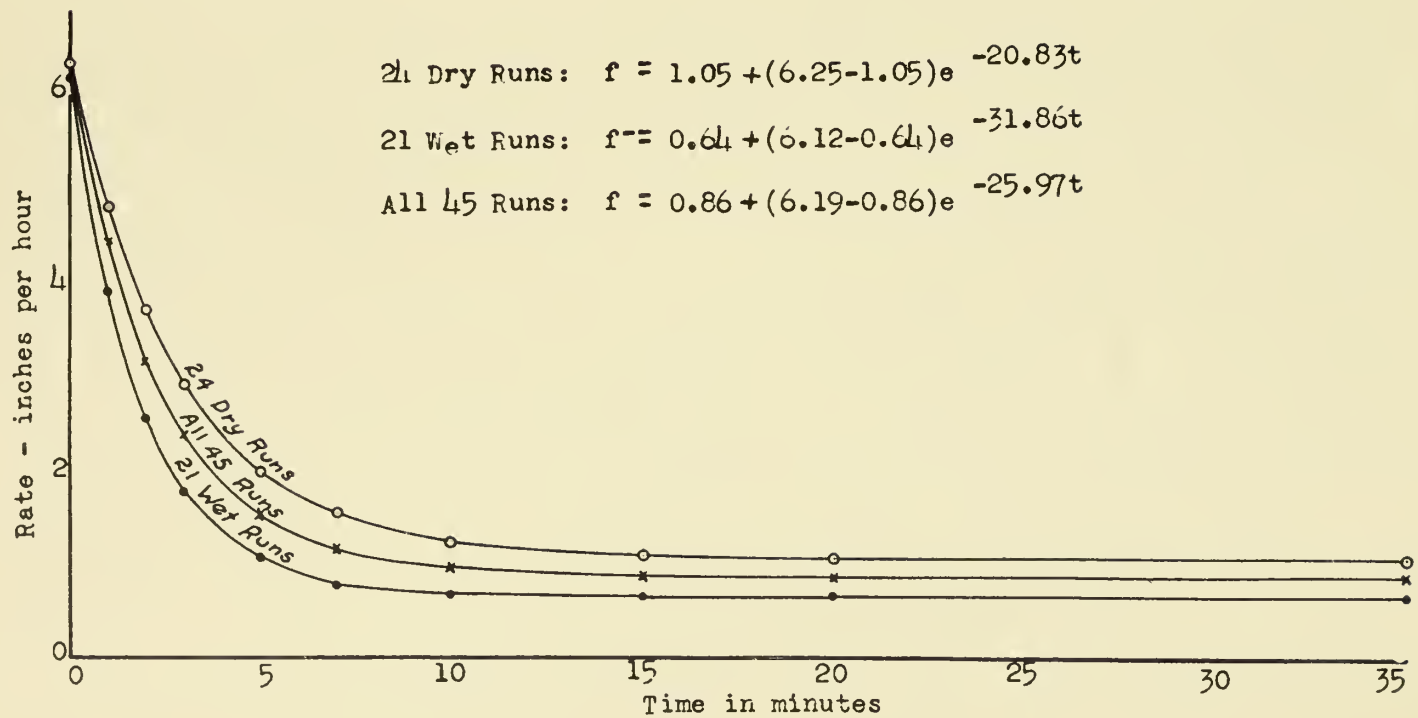


Figure 15.--Average infiltration capacity curves.

Relation of slope to infiltration: No consistent variation of the run-off coefficient K_a (in terms of δ) with increasing slope could be established from these experiments. This was probably due to the fact that the effect of slope is partly masked by seasonal variations but in the main it is due to variations in soil type, soil surface, and cover conditions concomitant with the different slopes. In dealing with natural watersheds, the ecological relationships must be carefully considered. Most individual soil types do not occur on a wide range of slopes without change, a ten percent range being perhaps above the average. Vegetative types likewise vary somewhat with soil types and topographic aspect.

The infiltration-capacities of soils occurring on low slopes (less than 3%) in this region seem to be much more variable and, when unprotected by a good vegetative cover, are probably lower than for soils occurring on steeper slopes. This is due to the fact that the flatter areas are subject to alluvial processes of deposition and removal and contain fine sandy, silty, and clayey soils which permit ready infiltration of water only when their surfaces are kept in a favorable condition. When a good growth of grass and plant litter cover these soils they may have higher infiltration-capacities than adjacent more steeply inclined and also more sparsely vegetated slopes. They may, as areas of natural water spreading, be able to absorb not only most of the rainfall but also considerable run-off from contributing slopes. When the natural balance has been upset, however, and the vegetative cover

has deteriorated due to erosion or some other cause these flat-lying soils often tend to puddle and seal over. Several of the experiments show large variations in infiltration-capacities within a slope range of 1 to 3% on the same general soil type.

In order to eliminate variables due to soil type and cover, experimental data for sites, 5, 6, and 7 (Table 2) can be best used to note the relationship between slope and infiltration. These three sites in themselves perhaps do not furnish sufficient data to establish conclusively a slope infiltration relation but they are typical of other experiments conducted recently and not included in this report. These sites having slopes of 5.0, 9.0, and 13.7% are on the same soil type located within 150 yards of each other on the same exposure, and have nearly the same soil surface conditions. They are nearly identical from the cover standpoint, being bare except for very little annual plant debris and some leaves from surrounding creosote bushes. No significant relationship between slope and infiltration is evident in these sites nor in other sites not reported in this series of experiments, all tending to bear out the conclusions of other experimentors such as Duley and Hays[1] and Neal.[2] It would thus appear that other factors

[1]Duley, F. L., and Hays, O. E. The effect of the degree of slope on run-off and soil erosion. Jour. of Agric. Research 45:349-60 (1932).

[2]Neal, Jesse H. The effect of the degree of slope and rainfall characteristics on run-off and soil erosion. Missouri Agric. Exp. Sta. Res. Bul. 280 (1938).

including cover, soil surface and profile being equal, no significant correlation exists between slope and infiltration.

The roughness factor: The roughness factor n given in Table 2 has the same general meaning as the roughness factor n in the Manning formula for flow in channels. However, in the latter case the resistance is chiefly that of true boundary rugosity, while in the case of surface run-off the resistance due to the surface itself may be relatively small compared with the resistance due to eddies, ineffective slope, and vegetation or other surface obstructions such as stones and gravel characterizing the erosion pavement on many of the sites reported in these experiments.

It may be noted that values of n for the greater number of experiments are less than 0.100 and in many cases are less than 0.050 or of the same order as the values of n appurtenant to stream channels. Where high values of n exist such as those above 0.10, a large amount of resistance is indicated due to causes other than boundary rugosities. These facts taken together indicate (1) that the true surface or boundary resistance due to rugosity on these soils is of the same order as that for natural stream channels, (2) that the highly increased resistance occurring in a number of cases is due to surface obstructions which may be either vegetal cover, plant debris, or stones and gravel. The latter would have the same effect as grass in increasing frictional retardation but in addition would materially reduce the effective cross section, and the result would be a large increase

in the value of n, which is computed on the basis of the entire cross section being effective.

While the particular sites on which these experiments were made had sparse covers of vegetation and in some cases had bare soils, it is apparent that even the limited amount of ephemeral plant growth together with scattered shrubs furnish debris which may have an important bearing on infiltration and run-off. Vegetal cover and litter may operate to increase the resistance in a variety of ways: (1) by subdividing the flow and greatly increasing the wetted perimeter; (2) by forming complete or partial debris dams on the soil surface, through which the run-off filters slowly, with greatly increased resistance and loss of effective head or slope. The conditions at some of the sites where these experiments were carried out seem to have been peculiarly adapted to the occurrance of the latter phenomenon. It was noted on many plots that while little plant growth and litter were prominent on the surface before the initial run, after an application of three inches of rain debris dams were built up in various parts of the plot from plant material which had originally been scattered on the surface and had been partially incorporated in the surface soil horizon.

The soil surface itself when in a dry condition assumes a certain roughness due to trampling effect of either one or a combination of livestock, wildlife, or humans, shrinkage during the drying process, as well as other factors. Roughness due to these

influences as well as that of scattered plant materials is somewhat ironed out after an application of rain. The loose plant debris becomes segregated into rows and dams and the attached material is more or less lined up with the direction of flow down the slope, thus offering less total resistance to run-off. Indications are that the larger depressions which are most evident in observing depression storage are somewhat filled in with soil during the first application of rain on a plat and are thus less effective during the wet run.

The roughness factor has an important bearing in relation to run-off retardation, since high values of the roughness factor correspond to low values of the run-off coefficient K_s and low run-off intensities and increased duration of rain necessary to bring the run-off intensity up to equality with the supply rate, $i - f_c$, in fact, it is through increased resistance to surface run-off that vegetation acts in part to reduce soil erosion and promote infiltration. This comes about partly through reduced velocity of overland flow, partly through increased depth of surface detention and consequent increased infiltration of water remaining on the ground when rainfall excess ends.

Seasonal variation of infiltration-capacity: Normal climatic conditions in southern Arizona include two rainy seasons — the summer and winter. The former usually extends from July through September and the latter from December through March. The late spring and fall are very dry especially the spring which during many

years is practically rainless. This means that surface soils of the lower elevations are often nearly in an air-dry condition just preceding the summer rains. Usually the average soil moisture is maintained at a higher level during the winter rainy season than during the summer since little water is lost as run-off during the low intensity rains, evaporation is much lower, and plant growth with resulting transpiration losses is less active during the winter.

It is not believed that the series of experiments reported in this paper lend themselves well to a study of seasonal variations of infiltration-capacity since experiments were conducted on different sites and soils throughout the year. Later experiments, however, are in progress in which repeat runs are being made on the same site. To date a number of runs have been made on several sites during the summer and again during the winter, the initial soil moisture being nearly the same and in most cases the infiltration-capacity is definitely lower during the winter (cooler months) than during the summer (hotter months).

Part of the seasonal variation of f_c is probably due to temperature and part to biological activities within the soil which are influenced by temperature as well as by soil moisture. Activities of insects and other soil fauna as well as microbiological activities are largely controlled by soil moisture conditions as well as temperature. Studies in progress at the University of Arizona indicate that microbiological activity in range soils is

much greater during the hotter than during the cooler periods of the year and also increases during periods of higher soil moisture.

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